THRUST AUGMENTATION FOR TOMAHAWK CRUISE MISSILE

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ABSTRACT

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A multiple orifice canister baseplate was designed for the Tomahawk Cruise Missile to achieve required thrust augmentation characteristics during surface ship and ground launches. This new baseplate will replace the present single orifice baseplate which was analytically determined unsatisfactory under extreme launch conditions. Scaled model tests using room temperature air were conducted and flight test data were utilized to predict the discharge characteristics of new baseplates under the real launch conditions. These discharge characteristics were used in a computer program simulating a Tomahawk launch to predict the launch dynamics and thrust augmentation characteristics. The improved thrust augmentation with the new baseplate will assure a successful Tomahawk missile launch for the full range of ground or ship launch conditions.

INTRODUCTION

Extension of the Tomahawk Cruise Missile missions to include surface ship and ground launch capability has required special launch considerations. The initial Tomahawk missile and its booster were designed for an underwater boost phase which required an initially low thrust during underwater travel followed by rapid increasing thrust after broach. To allow use of the booster without redesign for ship and ground launch capability, a technique to augment initial booster thrust was developed. Thrust augmentation is achieved by restricting the flow of booster exhaust gas with the baseplate of the launch canister. The resultant pressure build up in the canister provides additional force to accelerate the missile to a required launch velocity.

The thrust augmentation and resulting missile motion, however, have to meet various requirements to be satisfactory. Those requirements are imposed by the structural limit of the canister, the guidance package acceleration restrictions and considerations for successful flight after the launch. Futhermore, a particular design should be applicable for a wide range of launch conditions defined by combinations of launch parameters. The significant parameters are: booster grade and grain temperature, friction drag, canister pressurization, missile weight, launch angle and cover installation.

Various single orifice baseplates have been flight tested with a final selection of 4.9 in diameter. Even though General Dynamics has successfully launched several Tomahawk missiles with this baseplate, we have predicted for some time that a single orifice baseplate cannot satisfy all the launch requirements under extreme launch conditions. This prediction was based on our computer simulation of Tomahawk launches which predicts thrust augmentation and launch dynamics during a canister launch.

An important input for the computer simulation is the discharge coefficient of the orifice(s) at the baseplate. For a single orifice plate, it was well established from flight test correction. For other orifice configurations, they were not known. Scaled model tests were conducted to determine the discharge coefficients with various baseplate orifice configurations. The results from these model tests and the discharge coefficient during a flight test (with single orifice) were used to predict the discharge coefficient. The predicted discharge coefficients were in turn used in a computer program to simulate a Tomahawk launch. A new baseplate orifice configuration was selected based on the thrust augmentation and launch dynamics information derived from this simulation.

DESIGN CRITERIA

The goal of this design study was to find a baseplate orifice configuration which generates a satisfactory thrust augmentation under any platform launch conditions. A launch condition is defined by combination of launch parameters whose extremes are given in Table 1.

TABLE 1

Parameters	Extremes
Booster Grade & Grain Temperature:	110°F, +2 σ to -20°F, -2 σ
Missile Weight:	3000 lb_m to 3500 lb_m
Launch Angle:	34° to 90°
Cover:*	GDC or MMC + GDC
Friction Drag:	200 lb_f to 2000 lb_f
Canister Pressure:	3 psig to 7 psig

* GDC refers to a General Dynamics Convair designed fly-through cover which is installed on the Tomahawk launch canister. MMC refers to a Martin Marietta Corporation designed fly-through cover which is installed in their Vertical Launch Systems (VLS) canister. When Tomahawk launches from the VLS it must penetrate both covers.

A combination of minimum parameter values and maximum booster constitutes a favorable launch condition while those from the upper limits and minimum booster result in an unfavorable launch condition.

The thrust augmentation and resulting missile motion must meet several requirements to be considered satisfactory. These requirements are shown in Table 2.

TABLE 2

Maximum Baseplate Pressure (psig)	120
Maximum Acceleration (g)	11
Minimum Exit Velocity (ft/sec)	85
Maximum Time in Canister (sec)	0.8

The first two requirements provide an upper limit of the thrust augmentation usually under a favorable launch condition while the next two requirements constitute a lower limit which are applicable to an unfavorable launch condition.

The thrust augmentation problem with a single orifice baseplate arises when the missile displacement (x) is small. Figure 1 shows the exhaust plume-baseplate relationship. The booster exhaust plume vs orifice configuration at a small x is such that a large portion of the exhaust gas escapes through the orifice unrestricted. After this initial stage (x >1.5 ft), the thrust augmentation is predictable and adequate. Reducing the orifice size will improve the thrust during the initial stage but this will result in excess baseplate pressure, and also an acceleration which exceeds the limits. The desirable thrust augmentation characteristic is an immediate pressure build up during the initial stage, as would be expected of a small orifice baseplate followed by constant or slightly decreasing pressure as the launch continues.

COMPUTER SIMULATION OF A TOMAHAWK LAUNCH

A computer program has been developed in house by the author which simulates the Tomahawk launch dynamics. This program has its base on Newton's 1st Law (F = ma) and considers all the relevant parameters involved during a launch. The forces considered are:

- Booster Thrust
- Forces to Break Cover(s)
- Force Due To Compression of Gas Between Cover and Missile
- Drag Forces Due to Seal and Cover(s)
- Force Due to Thrust Augmentation Pressure

The input variables are:

- Missile Weight
- Launch Angle
- Atmospheric Pressure
- Canister Pressurization
- Cover Specification
- Discharge Coefficient of the Baseplate Orifice
- Booster Discharge Mass Flow and Thrust

The discharge coefficient of the baseplate orifice is an important parameter that controls the thrust augmentation performance. An accurate discharge coefficient is vital for a reliable simulation of the Tomahawk launch. The discharge coefficient of a baseplate during a Tomahawk launch is a complex parameter which depends on the baseplate-booster nozzle distance, exhaust plume geometry and orifice configuration and must be determined experimentally.

This program has provided successful pre-launch predictions for many previous Tomahawk launches with a single orifice baseplate. An accurate prediction has been vital for the canister and baseplate design and the performance of a new baseplate will be predicted with this computer simulation once the discharge coefficient is known.

PROCEDURE OF STUDY

After careful examination of the present problems with a single orifice baseplate it was concluded that a multiple orifice baseplate, when orifices are properly distributed, may possibly generate the desired thrust augmentation during the launch. The discharge coefficient of this baseplate must be determined experimentally. The present design study was to be accomplished in three steps.

a. Model tests with room temperature air
b. Estimation of the discharge coefficient during a Tomahawk launch with new baseplate
c. Computer simulation

The model tests were conducted with a 0.344 scale model baseplate and room temperature air. See Figure 2 for schematics of test procedures. Internal studies (Reference 1) conducted previously indicated that the shape of a hot gas plume is considerably different from a cold air plume. The difference in plume shape certainly will affect the discharge characteristics at the baseplate orifice(s) and the hot gas discharge coefficient must be estimated from cold air-model test results and hot gas-flight test results.

Several candidate baseplate orifice configurations were examined before two basic configurations were selected for the model test. These orifice configurations are shown in Figure 3. The preliminary phase of the study determined a superior basic orifice configuration (Configuration I or Configuration II). In the final phase of the study, the orifice distribution was systematically changed within the basic configuration selected to determine an optimum orifice distribution.

MODEL TEST (PRELIMINARY PHASE)

The model test was composed of scale tests and static simulation tests. The scale tests were conducted to find the discharge coefficient of the baseplate orifice when flow was from a large plenum. The results of these tests represent the discharge performance of the baseplate when the missile displacement is large. The discharge coefficient is calculated from:

$$\dot{m} = C_D \ A_{orifice} \sqrt{\frac{2k}{k-1} g_c \ P_1 \rho_1 \left[\left(\frac{P_2}{P_1} \right)^{2/k} - \left(\frac{P_2}{P_1} \right)^{\frac{k+1}{k}} \right]}$$

for $P_2/P_1 > 0.528$

and

$$\dot{m} = C_D \ A_{orifice} \ P_1 \sqrt{\frac{k}{RT} g_c \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \quad \text{for } P_2/P_1 < 0.528$$

where

R = gas constant $\left(\frac{ft \times lb_f}{lb_m \times {}^\circ R} \right)$

$A_{orifice}$ = total area of the orifice (ft^2)

k = adiabatic exponent (dimensionless) = 1.4

P_1 and P_2 are baseplate pressure and ambient pressure (lb_f/ft^2 abs), respectively

C_D is a discharge coefficient

g = gravitational conversion constant (lb_m-ft/lb_f - sec^2) = 32.174

ρ_1 and T_1 are density (lb_m/ft^3) and temperature (R) of air in the baseplate cavity, respectively

Figure 4 shows the discharge coefficient of three baseplates as a function of plenum pressure. Two things are notable. First, the discharge oa air through Configuration II baseplate is most efficient while the discharge is most inefficient for Configuration C. This difference between different configurations is substantial and will affect the thrust augmentation accordingly. Second, the magnitude of discharge coefficient seems to indicate that the orifices perform more or less like a short pipe, rather than a sharp-edged plate. The discharge coefficient of a sharp-edged plate is much smaller ($C_D = 0.6 \sim 0.7$).

The general shape of the discharge coefficient plots seems to agree with previously reported sharp-edged single orifice discharge coefficient (see Reference 2). The discharge coefficients measured with multiple orifices are reported by Kolodzie, Jr. et al (Reference 3). Their discharge coefficients and the present test results showed excellent agreement for similar pitch-to-hole diameter ratio and plate thickness to hole diameter ratio.

The importance of the scale test is twofold. First, these test results indicated reliability of the present measurements. Second, the discharge coefficients at high pressure provide the asymtotic values for the test results in the static simulation test. The distance between the baseplate and nozzle tested in the static simulation test covers up to 8 in. This test result with Configuration O is especially essential since the discharge coefficient from the static simulation test doesn't converge fully in the test range. The variation of C_D with the baseplate pressure is not as significant as it may look because the baseplate pressure reaches the maximum pressure (75 $\sim$ 110 psig) in a fraction of second ($\sim$ .1 sec) and within the pressure range, the variation of C_D was ± 1.5%.

Static simulation tests were conducted with a simulated nozzle in place. The static simulation test measured the mass flow rate as a function of nozzle baseplate distance and of baseplate pressure. Discharge coefficients are calculated by the same equations used for scale test. The baseplate pressure (P_1) is not the only parameter that drives the discharge as seen from the discharge coefficient which is larger than unity for small X. This is due to the definition used to determine the discharge coefficient. Because of the convergent-divergent nozzle used, there is a supersonic core with a pressure distribution across the orifice which, if accurately measured, would provide an integrated value which would result in a discharge coefficient < 1. The test results are shown in Figure 5.

ESTIMATION OF TOMAHAWK DISCHARGE COEFFICIENT

The present test results are obtained from scale model - cold air tests. The thrust augmentation of candidate baseplates may be properly compared only when the discharge coefficients during a Tomahawk launch with these baseplates are known. The present section describes a scheme predicting the Tomahawk discharge coefficient from available information.

Figure 6 shows the discharge coefficient during the T-16:2 launch in addition to the test results previously shown in Figure 4. The discharge coefficient of Configuration O is compared with that from Figure 5. The important features revealed from this comparison are:

a. The peak discharge coefficient during the Tomahawk launch is approximately 50% of that of cold air. This indicates that the hot-gas plume is larger than the cold air plume.

b. The discharge coefficient of Tomahawk launch varies gradually around the peak C_D. This may indicate that the plume boundary of hot gas is not as sharp as that of cold air.

c. It takes twice as much distance for the hot gas discharge coefficient to drop to that of cold air.

These comparative features were used to predict the discharge coefficient of Tomahawk launch with new baseplates which are shown in dotted lines in Figure 6. The accuracy of these C_D predictions, especially that of Configuration I, may be questioned. Slightly different predictions were made and resulting thrust augmentations were compared to find possible error in this prediction. Small variation of C_D at small R ($R < 0.15$) did not change thrust augmentation significantly. For large R, the discharge coefficient of hot gas is expected to be the same as that of cold air and it is this C_D that affects the thrust augmentation most. The hot gas discharge coefficient of Configuration II was predicted to be almost identical to or slightly lower than the cold air test result.

COMPUTER SIMULATION

The predicted Tomahawk discharge coefficients of new baseplates were used in the computer program to predict the thrust augmentation during the Tomahawk launches with new baseplates. Figure 7 shows the predicted baseplate pressures along with the T16:2 data. Some of the important characteristics are summarized in Table 3.

TABLE 3

	Configuration I	Configuration II
Minimum Baseplate Pressure (psig)	95	126
Maximum Acceleration (g)	9.23	12.5
Exit Velocity (ft/sec)	98.2	98.7
Time in the Canister (sec)	.42	.39

This comparison clearly indicated that Configuration I generates more desirable thrust augmentation. The thrust augmentation characteristics of Configuration I meet all the requirements previously given in Table 2 whereas the baseplate pressure and acceleration are too high with Configuration II. The launch parameter used for this prediction represents only an average condition. With extreme launch parameters, the baseplate pressure and acceleration will be even higher. Furthermore, the thrust augmentation characteristic of Configuration I may be easily changed by varying the orifice size at the center. With Configuration II, this is not possible.

Based on the results of this simulation, Configuration I was selected as the basic configuration (a small hole in the center and pheripheral holes) for the final baseplate. The orifice sizes would be optimized in the final phase of the study to make sure the thrust augmentation with the optimized baseplate meet all the requirements under the extreme launch conditions.

FINAL PHASE

Early into the present study, the computer predicted thrust augmentation characteristics of all the available launch cases were compared to determine two extreme launch cases, one most favorable and one most unfavorable. This comparison found that BGM-109B launch with a high performance booster is most favorable and BGM-109G with a low performance booster is most unfavorable. The launch parameters of two extreme cases are given as follows:

TABLE 4

Parameters	BGM-109B	BGM-109G
Missile Weight (lb)	3078	3510
Launch Angle (deg)	34	56
Booster	110°F, +2σ	-20°F, -2σ
Friction Drag (lb)	200	2000
Cover	MMC	GDC
Canister pressure (psig)	3	7

Using the estimated Tomahawk discharge coefficient of Configuration I (see Figure 6), the thrust augmentation of the two extreme cases was predicted. The baseplate pressures from this prediction are shown in Figure 8 and the important augmentation characteristics are shown in Table 5.

TABLE 5

Parameters	BGM-109B	BGM-109G
Maximum Baseplate Pressure (psig)	108	78
Maximum Acceleration (g)	12.1	6.9
Exit Velocity (ft/sec)	112.0	83.8
Time in Canister (sec)	.39	.51

The thrust augmentation characteristics of the two extreme cases revealed that the acceleration (12.1 g) is too high for the most favorable case and the exit velocity (83.8 ft/sec) is not quite enough for the most unfavorable case. It was known that a change of orifice configuration cannot reduce acceleration for one case and increase the exit velocity for the other simultaneously. A decision was made to reduce the maximum acceleration of the BGM-109B launch by enlarging the center hole. This will reduce the exit velocity of BGM-109G which already was low. However, a separate study indicated that this low exit velocity may be increased to the required velocity by reducing the friction drag (2000 lb_f) used for this case. A baseplate with 8% larger center hole but the same overall open area was selected to examine the effect of the center hole to overall exhaust performance and thus the thrust augmentation. This baseplate is called Configuration I-1 and shown in Figure 9.

Also examined during this phase of the study was Configuration I-2 which has five orifices. Configuration I-2 baseplate has an identical center hole as Configuration I-1 but has four peripheral holes. This configuration was examined to obtain a data basis for the five-hole configuration or a possible three-hole configuration. A baseplate configuration with less peripheral holes is considered necessary because of space restrictions for baseplate orifices. This new configuration is shown in Figure 9 also.

The exhaust performance of Configuration I-1 and Configuration I-2 are shown in Figure 10 along with that of Configuration I. Configuration I-1 shows considerably higher discharge coefficient for small X/D than Configuration I but Configuration I-2 shows very little difference. The discharge coefficients of the two new baseplates were virtually identical to that of Configuration I for large X/D ($X/D > .36$). The discharge performance of Configuration I-2 seems to indicate that the thrust augmentation of five-hole or three-hole configurations may

be similar to the seven-hole configuration if the size of the ce..ter orifice is kept unchanged and overall open area is maintained.

The thrust augmentation of Configuration I-1 is predicted in Figure 11 and the important augmentation characteristics during two extreme launches are given in Table 6.

TABLE 6

Parameters	BGM-109B	BGM-109G
Maximum Baseplate Pressure (psig)	99.1	70.1
Maximum Acceleration (g)	11.1	6.18
Exit Velocity (ft/sec)	111.3	81.7
Time in the Canister (sec)	.41	.54

The thrust augmentation characteristics in Table 6 indicate that Configuration I-1 is satisfactory except for the exit velocity of the BGM-109G launch. This exit velocity may be increased to a required velocity (85 ft/sec) if the friction drag (2000 lb) is reduced to approximately 500 lb, which may be possible in the final canister redesign.

CONCLUSIONS AND RECOMMENDATIONS

The present study showed that a multiple orifice baseplate, when orifices are properly distributed, can greatly improve the thrust augmentation characteristics over those of a single orifice baseplate. However, this study also showed that the selected baseplate orifice configuration will marginally meet the requirements under the extreme launch conditions. The margin of safety was smaller than desired.

A baseplate configuration I-4 (Figure 9) is recommended as the new baseplate configuration and the corresponding full scale baseplate is shown in Figure 12.

REFERENCES

1. Shih, P.K., "Computer Programs PLUME, Preheat and LTUBE," General Dynamics report DN-626, 1977.

2. Lea, F.C., Hydraulics, 6th edition, P.87, Edward Arnold and Co., 1938.

3. Kolodzie, Jr., P.A. and M. VanWinkle, "Discharge Coefficients ..rough Perforated Plates," AIChE Journal, Vol. 3, No. 3, 1959.

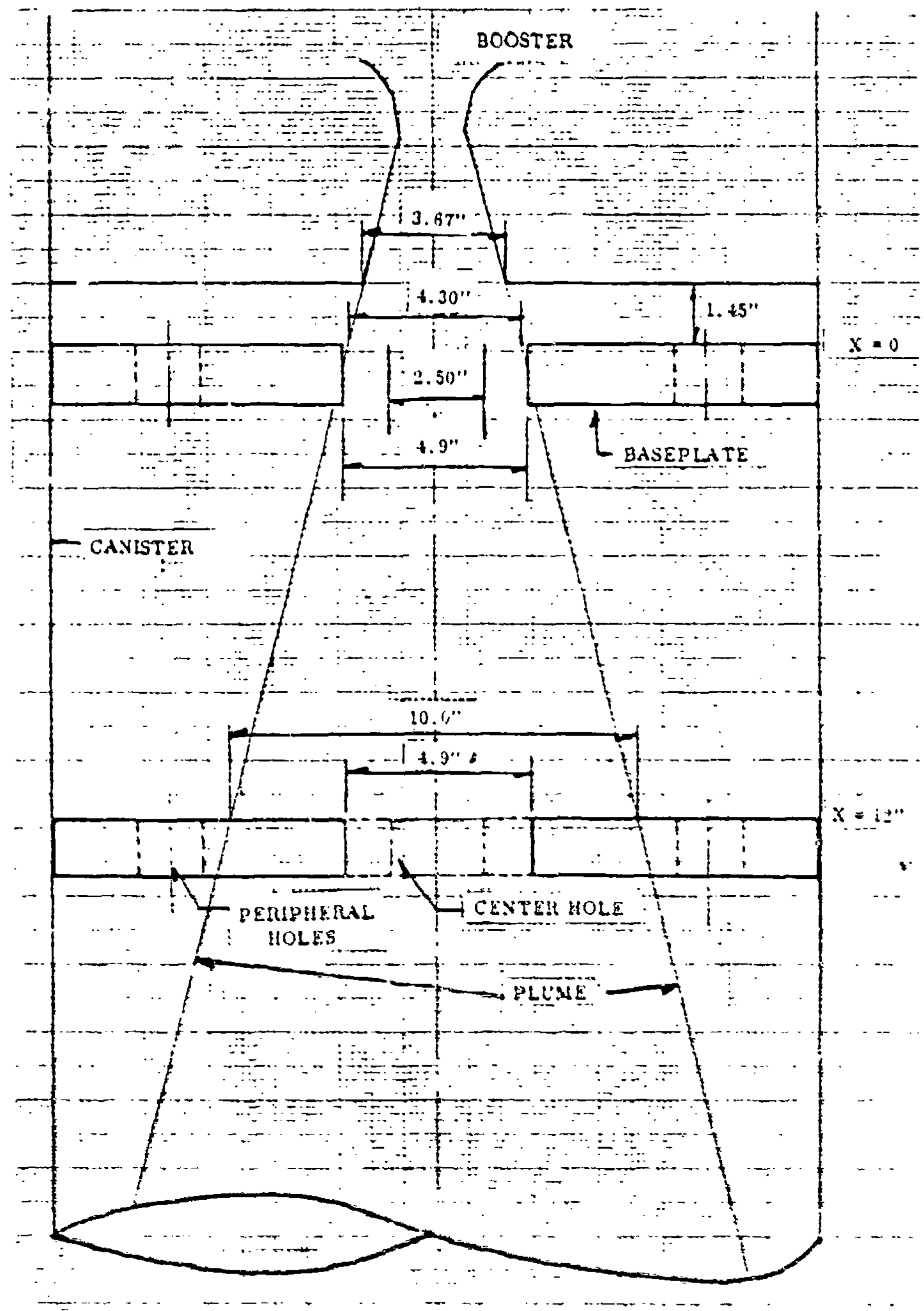

FIGURE 1. PLUME VS. BASEPLATE EXHAUST

1. SCALE TEST

   TO OBTAIN DISCHARGE COEFFICIENT OF VARIOUS BASEPLATE EXHAUST CONFIGURATIONS

2. STATIC SIMULATION TEST TO EXAMINE:

   a) P_1 VS. TIME FOR ℓ_1 = .52 IN.

   b) P_1 AS A FUNCTION OF ℓ_1

   c) DISCHARGE COEFFICIENT VS. ℓ_1

   TO SELECT EXHAUST OPENING PATTERN

3. DYNAMIC TEST TO OBTAIN:

   a) X VS. TIME

   b) P_1 VS. TIME

   c) ACCELERATION VS. TIME AND DISTANCE

   TO SIZE EXHAUST OPENING AREA FOR SELECTED PATTERN

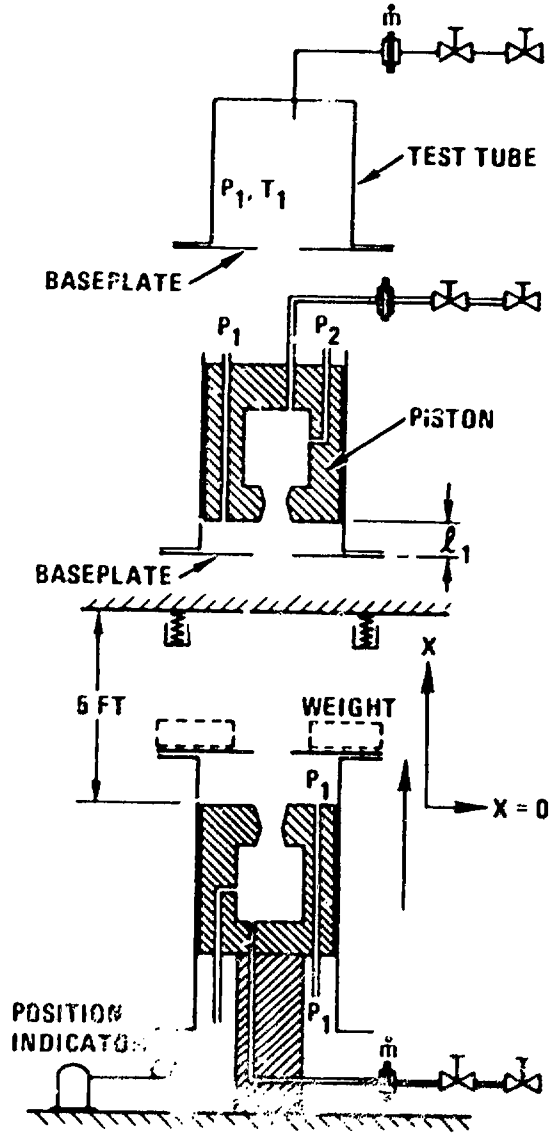

FIGURE 2. TEST PLAN (.3442 SCALE MODEL)

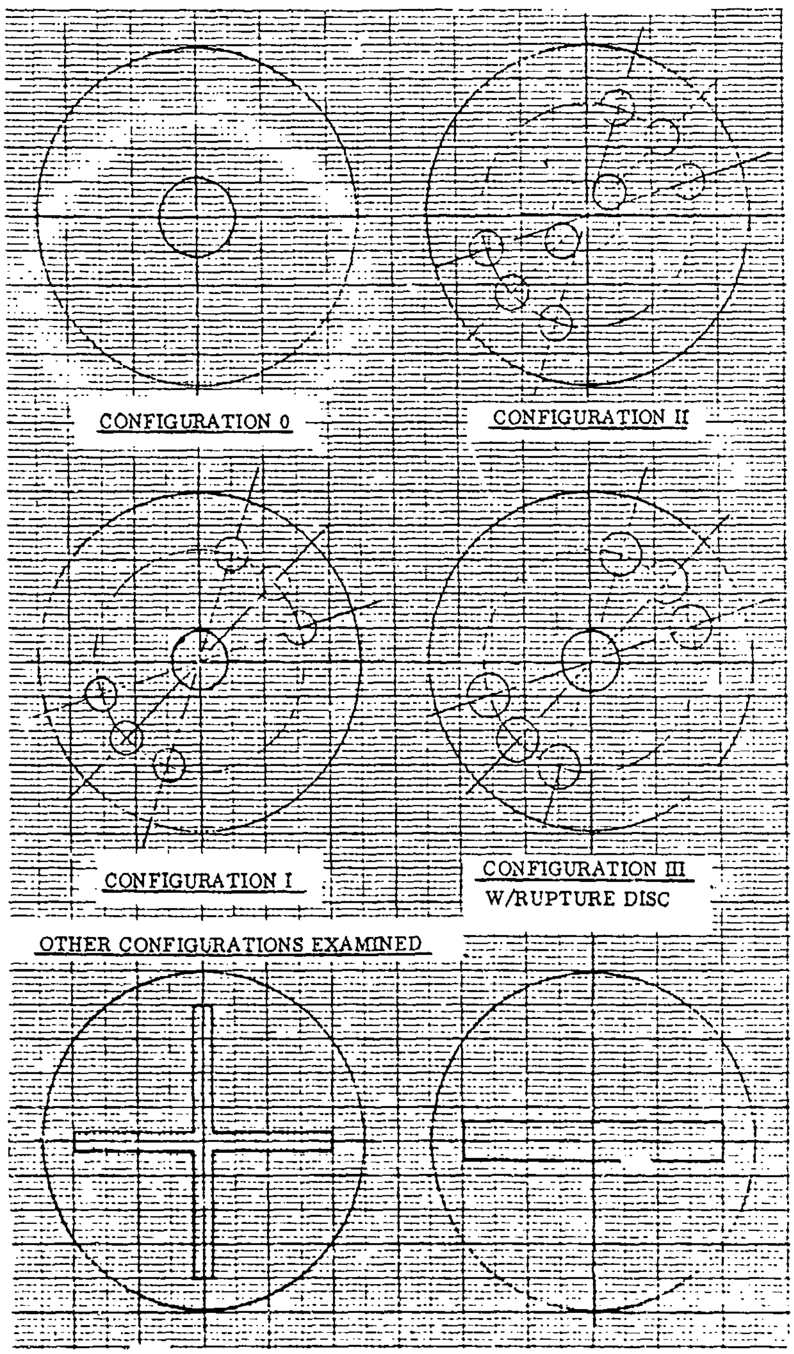

FIGURE 3. CANDIDATE BASEPLATE EXHAUST CONFIGURATION

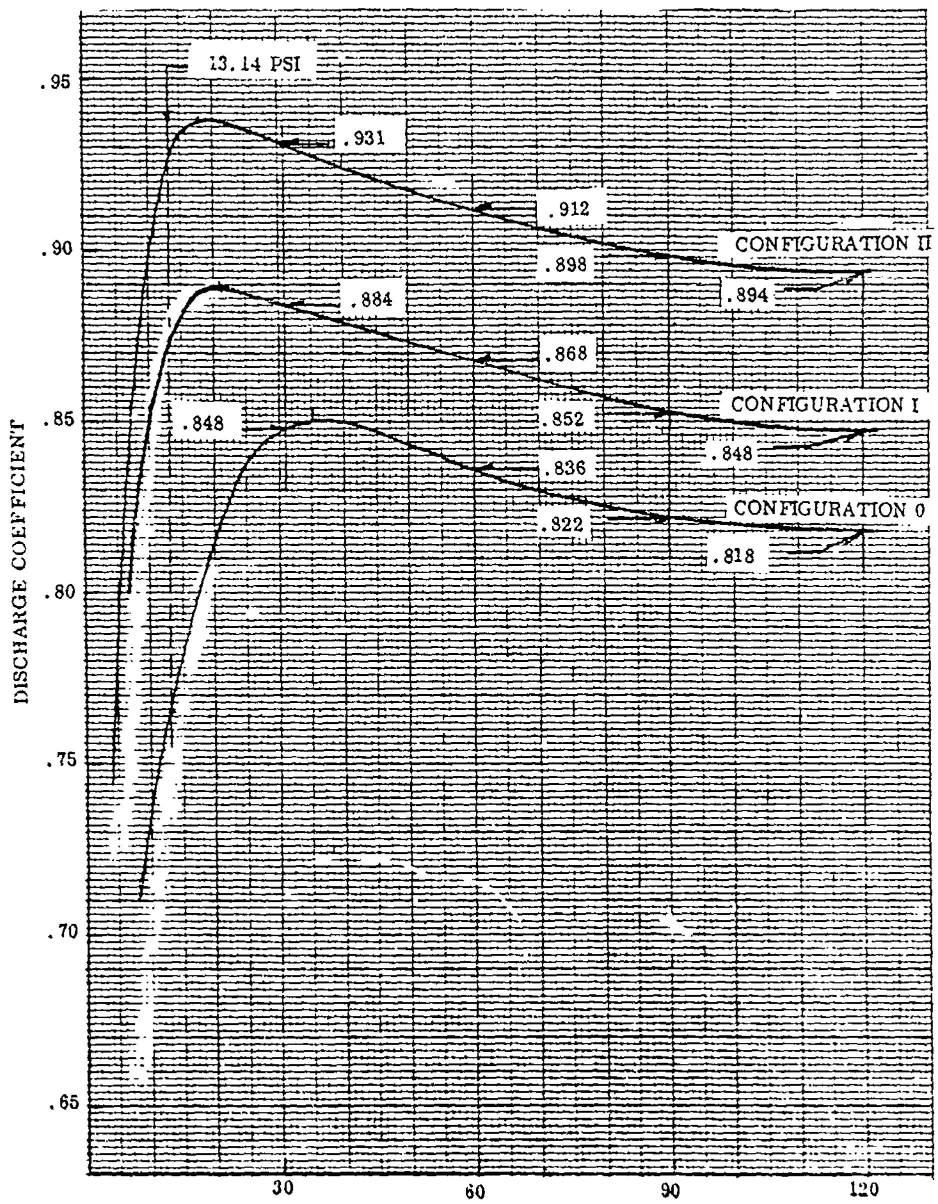

FIGURE 4. PLENUM PRESSURE (PSIG)

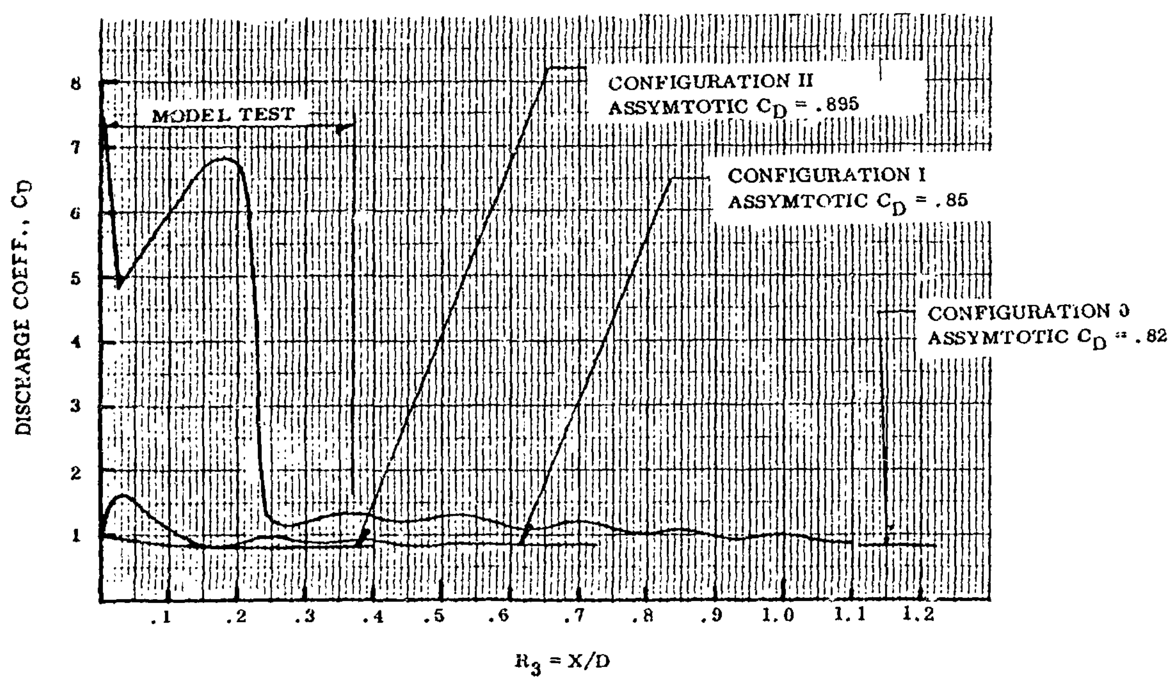

FIGURE 5. DISCHARGE COEFFICIENT FROM STATIC SIMULATION TEST

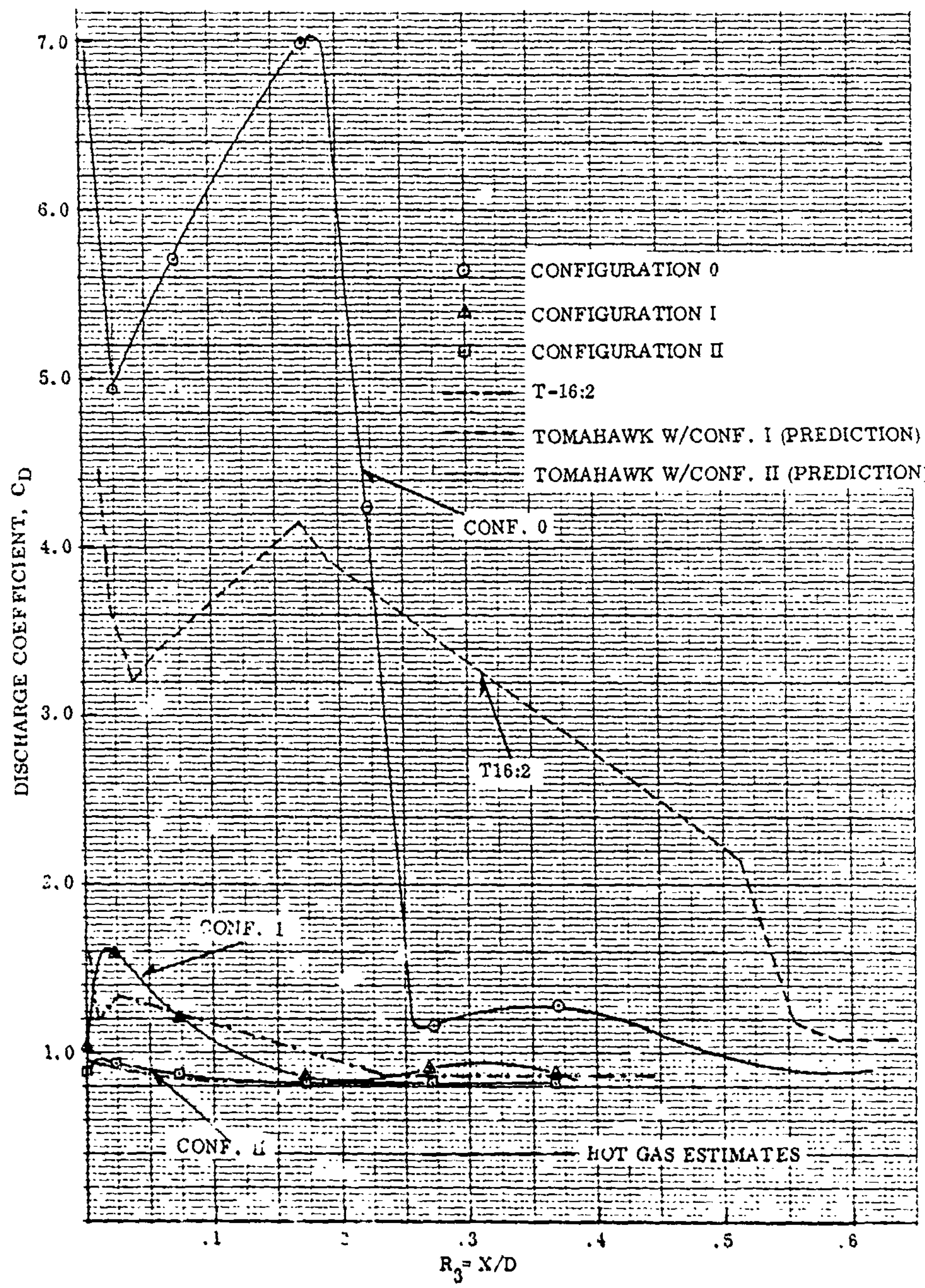

FIGURE 6. DISCHARGE COEFFICIENT, TEST VS PREDICTION

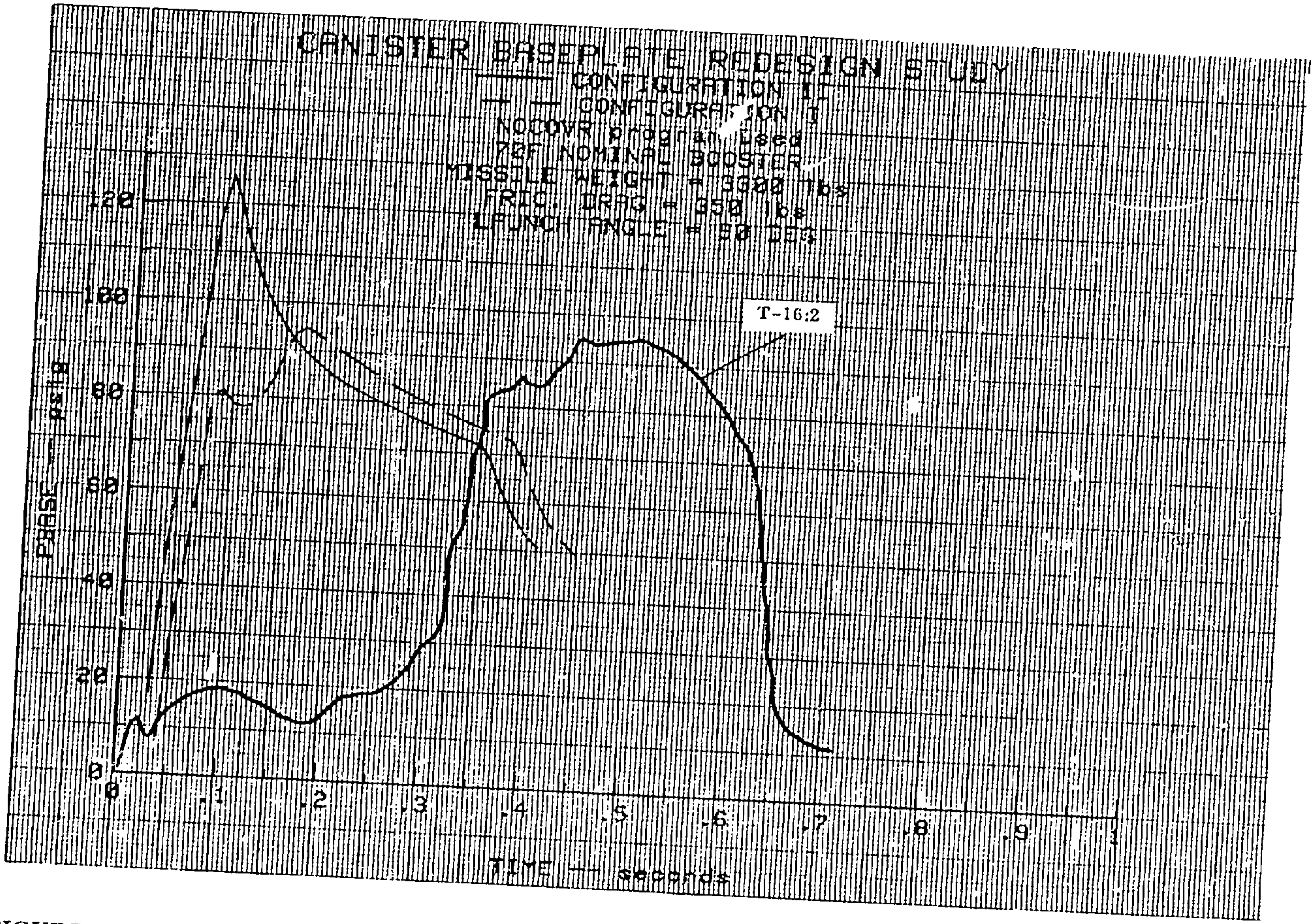

FIGURE 7. COMPUTER PREDICTED BASEPLATE PRESSURE AND FLIGHT TEST DATA

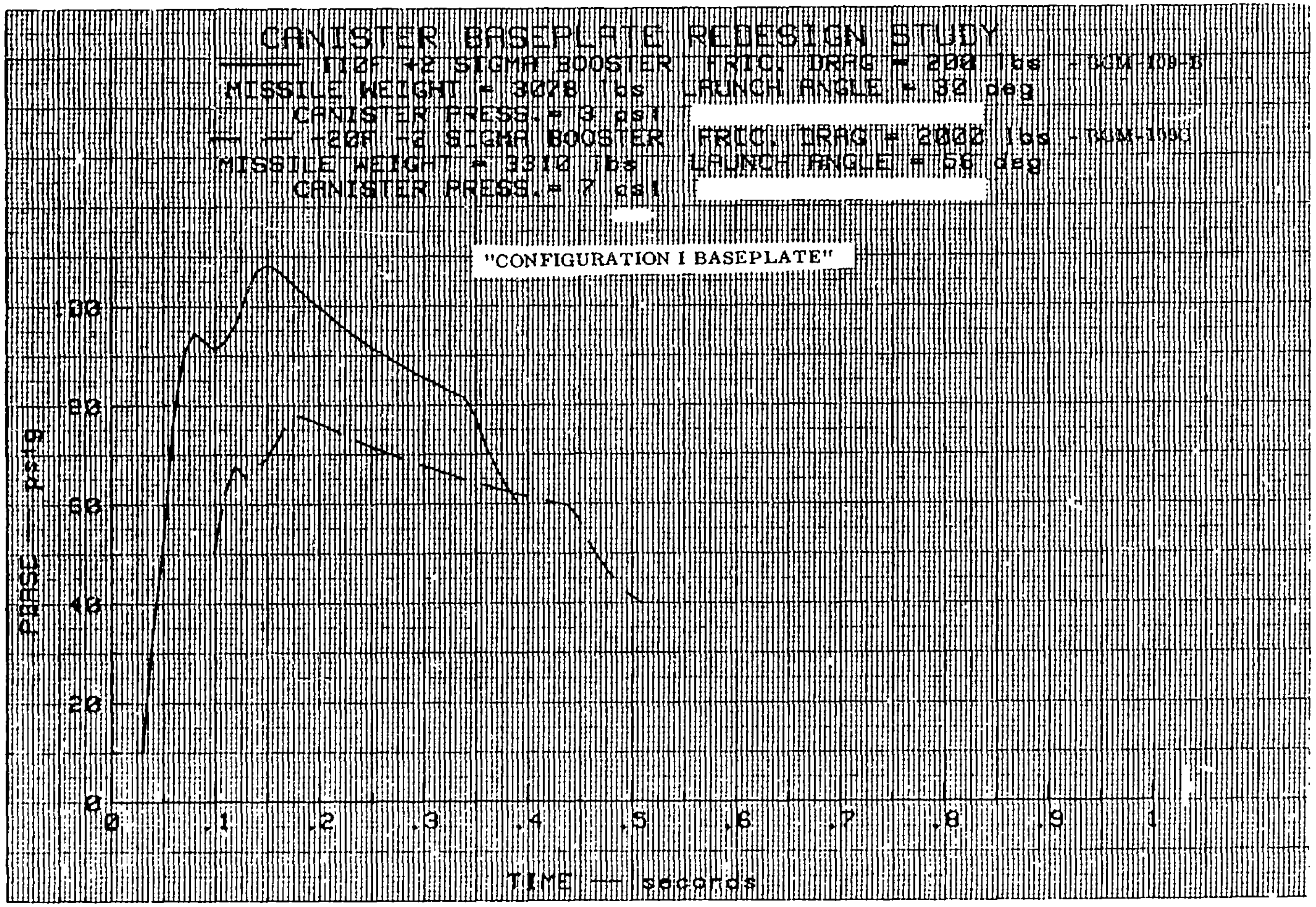

FIGURE 8. COMPUTER PREDICTED BASEPLATE PRESSURE FOR EXTREME CASES

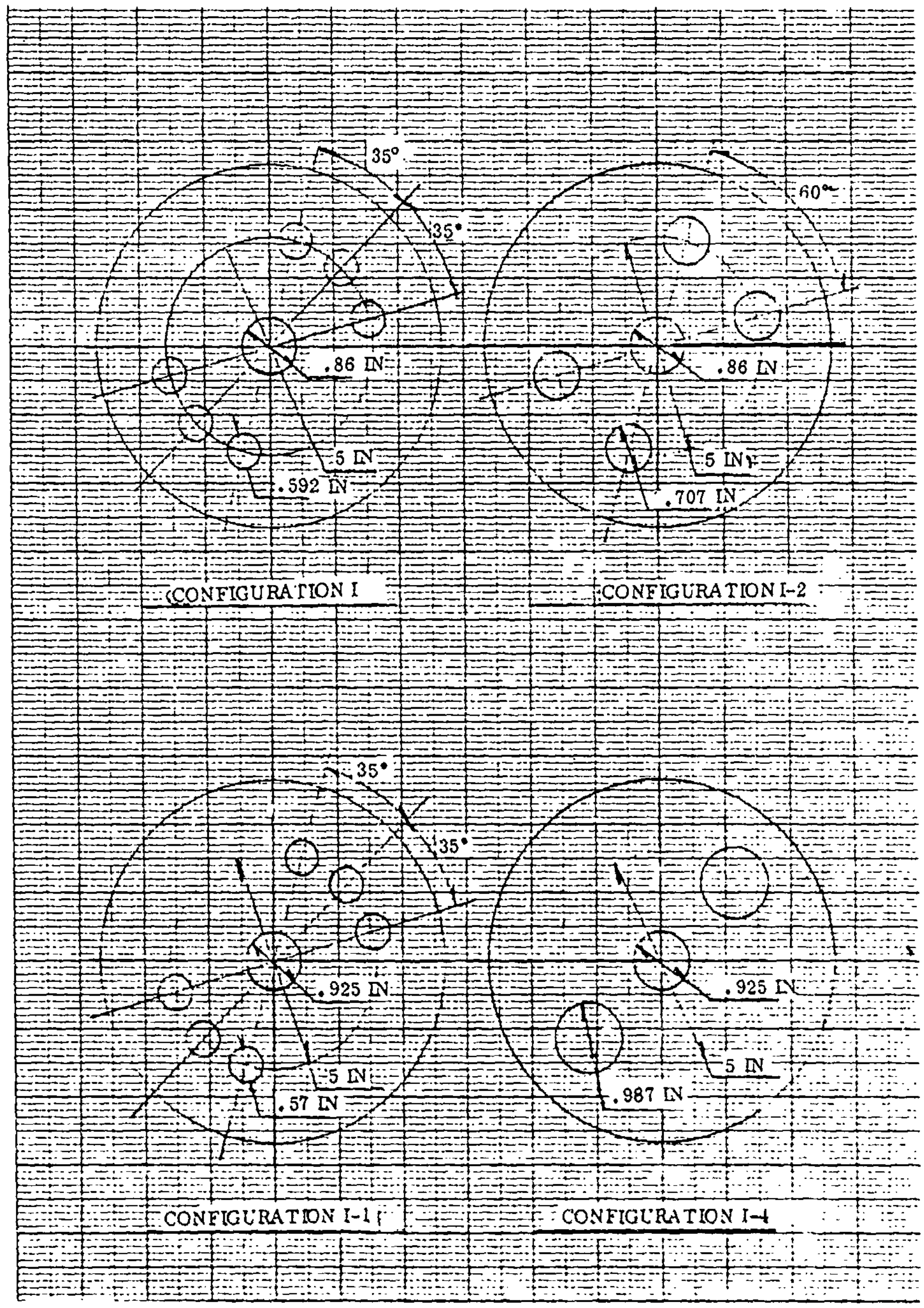

FIGURE 9. BASEPLATES TESTED DURING FINAL PHASE

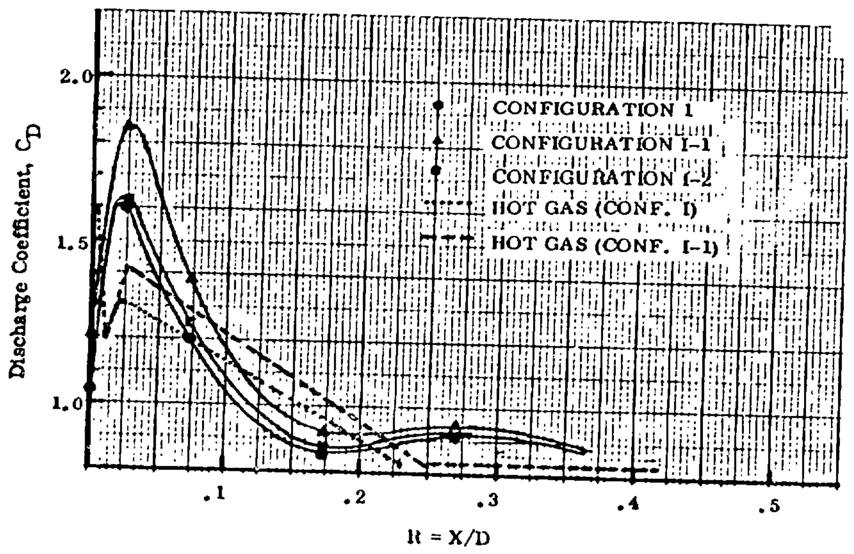

FIGURE 10. DISCHARGE COEFFICIENT FROM STATIC SIMULATION TESTS - FINAL PHASE

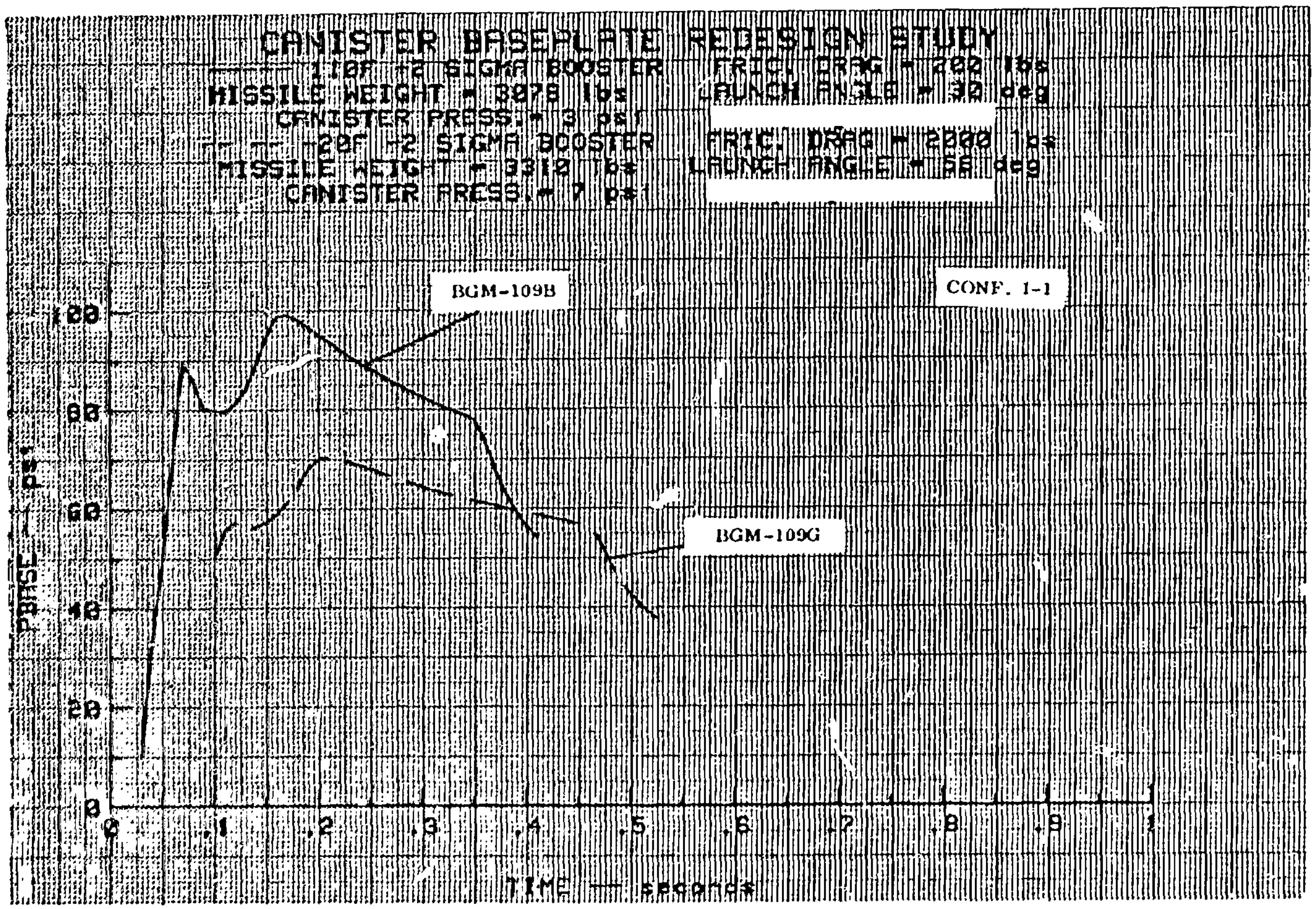

FIGURE 11. COMPUTER PREDICTED BASEPLATE PRESSURES AFTER IMPROVEMENT

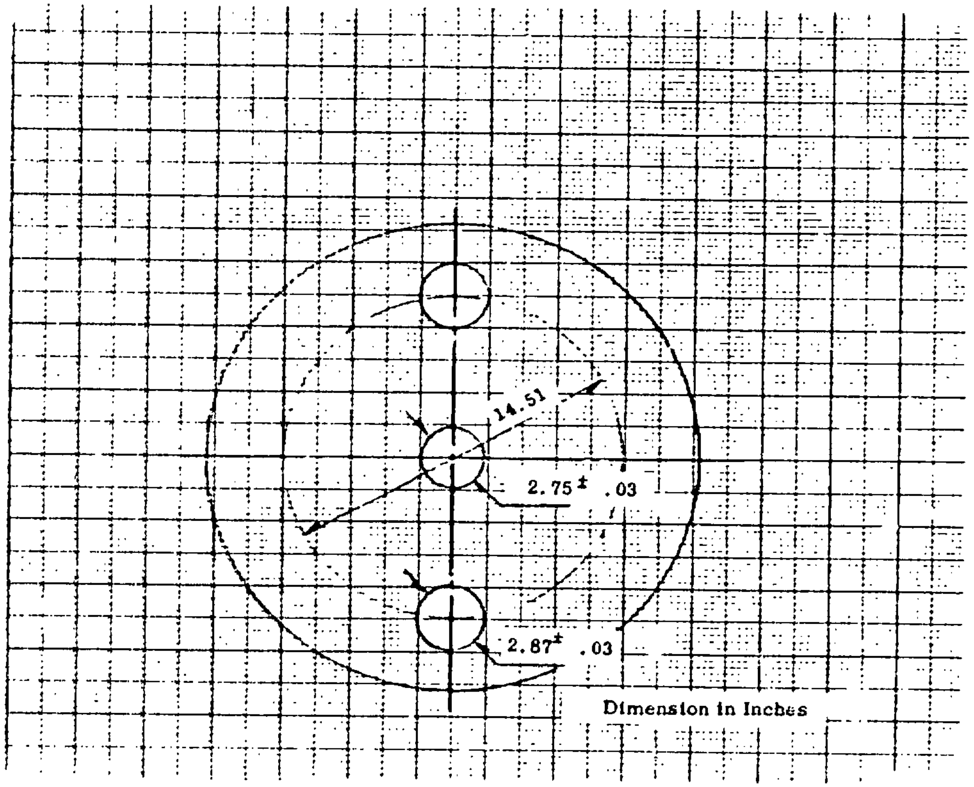

FIGURE 12. RECOMMENDED BASEPLATE ORIFICE CONFIGURATION